# LWR PHYSICS ANALYSES
# Np+Pu Assembly Designs
# Reduced Water Moderated Reactor

ANL

BNL

ORNL

M.Todosow

AFCI Semi-Annual Review Meeting

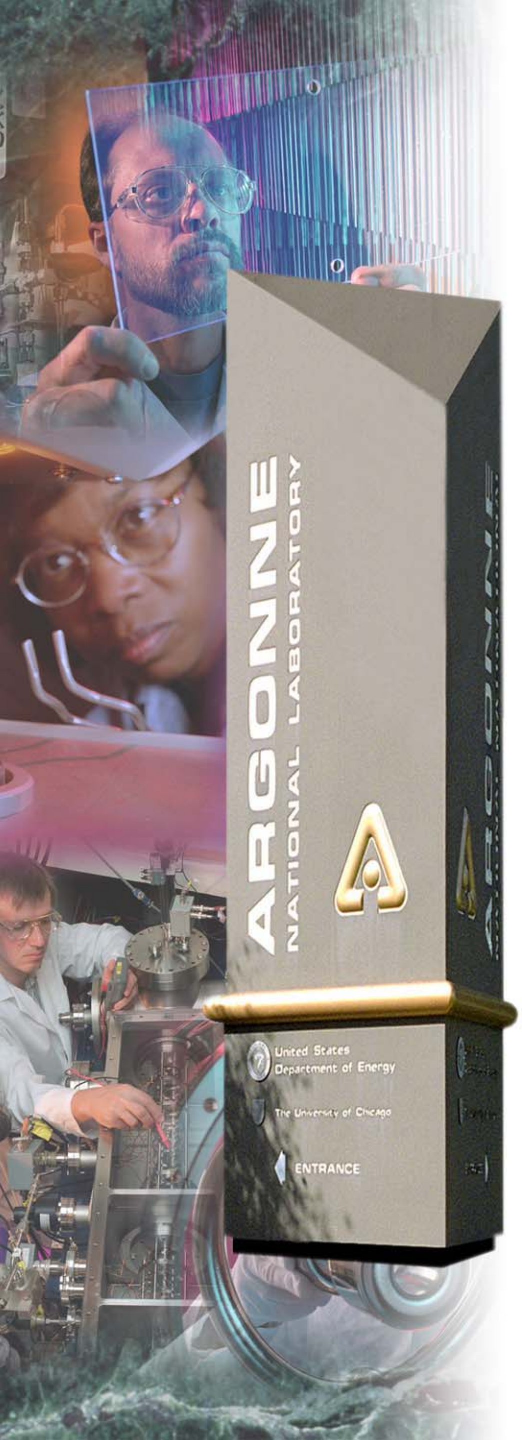
August 28, 2003

energy SCIENCES & TECHNOLOGY DEPARTMENT

BROOKHAVEN NATIONAL LABORATORY

# Activities

- Pu and Np+Pu MOX designs for W-17x17 assembly [ANL,BNL]
- Np+Pu MOX designs for CE System-80 16x16 Assembly [BNL]
- Reduced Moderator Water Reactor (RMWR) rod-cell and assembly benchmarking [ANL,BNL]
- Investigating burning of Am and/or Cm as targets in W 17x17 assembly [ORNL]




# Mixed-Oxide Assembly Design for Series 1 Transmutation

*John A. Stillman*
*Nuclear Engineering Division*

*AFCI Semi-Annual Meeting*
*August 25-28, 2003*

***Argonne National Laboratory***

Office of Science
U.S. Department of Energy

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# *Background*

- **Transmutation of actinides in existing U. S. reactors (LWRs) will reduce burden on systems just now in technology development**
- **Previous AFCI/AAA studies of mixed-oxide (MOX) fuel deployed in LWRs**
  - In FY01, actinide mass flow rates for an ALWR with a full-core loading of MOX fuel were evaluated. Separated plutonium and plutonium + minor actinides (for added proliferation resistance) fabrication scenarios were considered.
  - In FY02, the focus was “deep burnup” in existing LWRs using a heterogeneous $UO_2$/MOX pin loading in a “retrofittable” PWR assembly design (CORAIL concept)
    - *Complete destruction of self-generated plutonium achievable with multi-recycling*
    - *Minor actinide recycling limited to a few passes due to fuel-handling issues*
    - *Local power peaking requires loading optimization*
    - *Secondary transmutation system necessary in order to complete plutonium and/or minor actinide destruction and realize significant repository benefit*

# *Background*

- **Current study focused on MOX mono-recycling in partial-MOX cores in existing PWRs**
  - MOX assembly pin loading optimized to reduce power peaking
  - Evaluated reactivity coefficients (e.g., void, control rod worth) and transmutation performance
- **Source of transuranics assumed to be $UO_2$ burned to 50 GWd/MT + 10 years cooling; MOX fabrication for two separations scenarios considered**
  - Separated reactor-grade plutonium
    - *Largest portion of transuranics (TRU) in U. S. spent fuel stockpile is plutonium (~85%)*
    - *Loading separated plutonium maximizes destruction rate*
    - *Currently practiced in European MOX programs and intended for deployment in the U. S. weapons-grade plutonium disposition program*
  - Plutonium+neptunium recycle in MOX
    - *Postulated to provide additional proliferation resistance from $^{237}Np \rightarrow {}^{233}Pa \rightarrow 312$ keV g*
    - *Impact on assembly design and performance*

# Assembly and Core Design Parameters

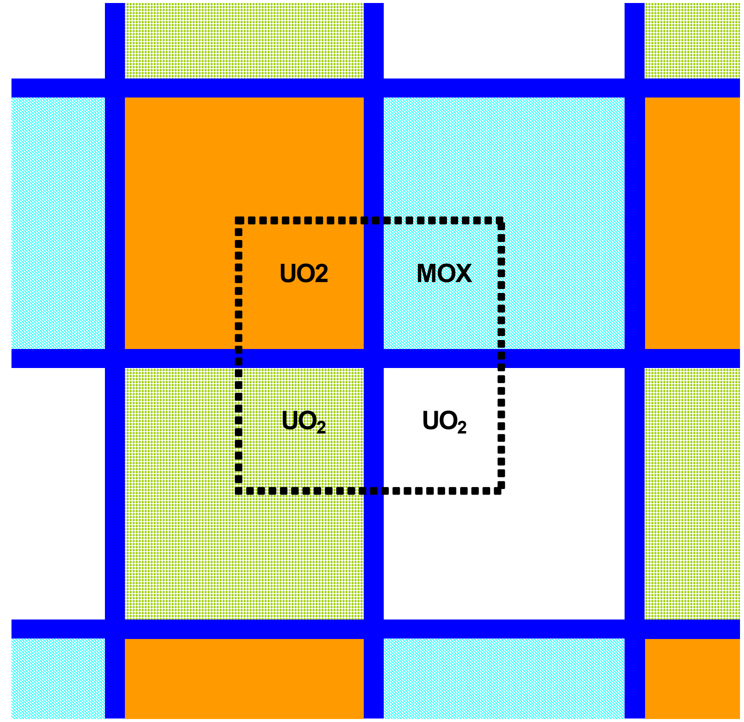
- **Fuel assembly design parameters similar to Framatome/COGEMA advanced Mark-BW assembly design; used for both $UO_2$ and MOX assemblies**
  - Uniform enrichment in $UO_2$
  - Enrichment zoning of MOX pins to control power peaking at MOX/$UO_2$ interface
- **Three-batch fuel management**
- **Target discharge burnup, 45GWd/MTHM**
- **Enthalpy-rise hot-channel factor ($F_{\Delta H}$) < 1.55 (typical)**

| | |
|---|---|
| Assembly size | 17x17 pins |
| Number of fuel pins | 264 |
| Number of guide tubes (GT) | 24 |
| Number of instrumentation tubes (IT) | 1 |
| Fuel rod pitch (cm) | 1.2598 |
| Inter-assembly gap (cm) | 0.08 |
| Fuel pellet radius (cm) | 0.4096 |
| Clad inner radius (cm) | 0.4178 |
| Clad outer radius (cm) | 0.4750 |
| Smeared fuel density (g/cm$^3$) (pellet at 95% T.D., 1.2% pellet dishing) | 9.88 |
| Fuel mass (kg HM/assembly) | 461.3 |
| Zircaloy-4 clad density (g/cm$^3$) | 6.5 |
| GT/IT inner radius (cm) | 0.5715 |
| GT/IT outer radius (cm) | 0.6121 |
| Specific power density (MW/MTHM) | 33.7 |
| Fuel temperature ($^o$K) | 900.0 |
| Cladding temperature ($^o$K) | 581.0 |
| Bulk coolant temperature ($^o$K) | 581.0 |
| Coolant density (g/cm$^3$) | 0.72 |

# MOX/$UO_2$ Color Set

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L | L | M | M | M | M | M | M | M | M | M | M | M | M | M | L | L |
| L | M | H | H | H | M | H | H | M | H | H | M | H | H | H | M | L |
| M | H | H | H | H | W | H | H | W | H | H | W | H | H | H | H | M |
| M | H | H | W | H | H | H | H | H | H | H | H | H | W | H | H | M |
| M | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | M |
| M | M | W | H | H | W | H | H | W | H | H | W | H | H | W | M | M |
| M | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | M |
| M | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | M |
| M | M | W | H | H | W | H | H | W | H | H | W | H | H | W | M | M |
| M | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | M |
| M | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | M |
| M | M | W | H | H | W | H | H | W | H | H | W | H | H | W | M | M |
| M | H | H | H | H | H | H | H | H | H | H | H | H | H | H | H | M |
| M | H | H | W | H | H | H | H | H | H | H | H | H | W | H | H | M |
| M | H | H | H | H | W | H | H | W | H | H | W | H | H | H | H | M |
| L | M | H | H | H | M | H | H | M | H | H | M | H | H | H | M | L |
| L | L | M | M | M | M | M | M | M | M | M | M | M | M | M | L | L |

L Low-enriched MOX pin (12)
M Medium-enriched MOX pin (68)
H High-enriched MOX pin (184)
W Water hole/guide tube (25)

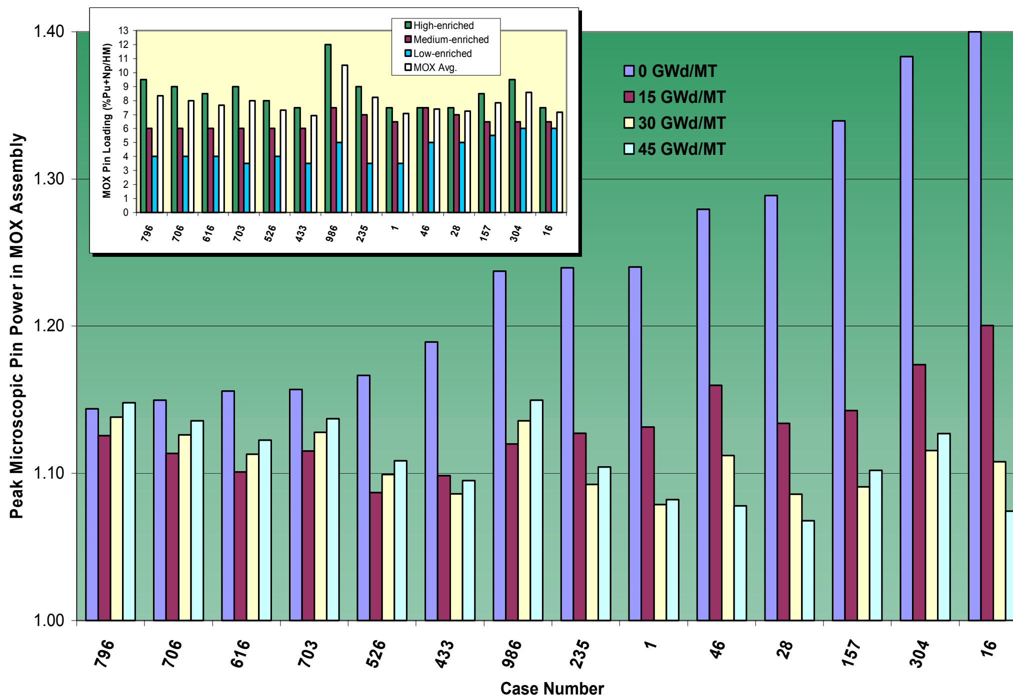



- Heterogeneous MOX pin layout currently utilized in French MOX program; similar to layout planned for weapons-grade Pu disposition
- "Color set" of 1 MOX, 3 $UO_2$ assemblies utilized optimization of MOX pin loadings to minimize local power peaking
- WIMS8 lattice depletion code (method of characteristics) with 172-group JEF2.2 library; $k_\infty$ = 1.035 approximates EOC state (3.5%$\Delta$k leakage)

# *MOX Enrichment Zoning Optimization*

- **Optimization of MOX assembly enrichment zoning performed using $MOX/UO_2$ color set evaluations**
  - MOX pin power is affected by presence of $UO_2$ neighbors, but is relatively insensitive to neighboring $UO_2$ assembly enrichment and burnup
  - Numerous color sets evaluated with variations on high-, medium-, and low-enriched MOX pin Pu or Pu+Np loading
  - Ranked by largest peak power in MOX assembly during lattice depletion

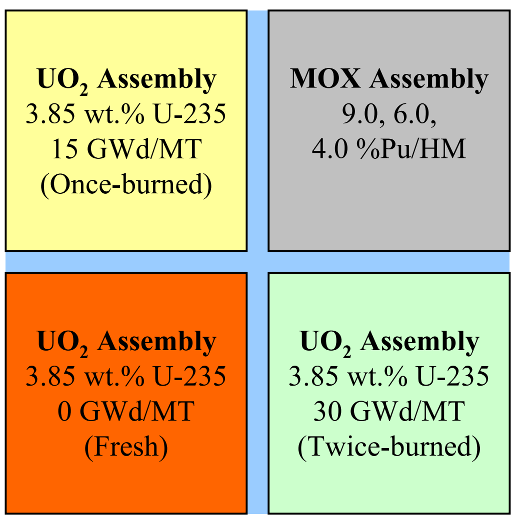
| Optimized MOX Pin Loading (%TRU/HM) | | | |
|---|---|---|---|
| | High | Medium | Low |
| Pu-MOX | 9.0 | 6.0 | 4.0 |
| Pu+Np-MOX | 9.5 | 6.0 | 4.0 |



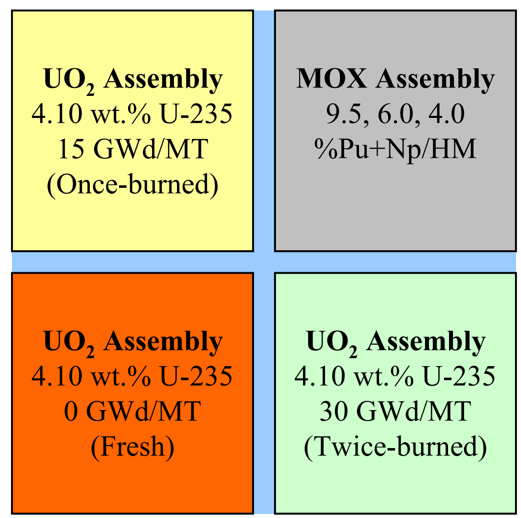

**Summary of Loading Optimization Search for MOX Fabricated with Pu+Np**

# Evaluation of MOX Fuel Performance

- **Calculations in present study were limited to lattice "color sets"**
- **Core environment simulated by surrounding MOX with fresh, once-, and twice-burned $UO_2$**
  - MOX assembly depleted from fresh to discharge conditions over 3 "cycles"
  - $UO_2$ assemblies "shuffled" at beginning of each cycle (15 GWd/MT accumulated burnup)
  - Cases with and without loading 12 $Gd_2O_3$-poisoned pins (6 wt.%) in fresh $UO_2$ assembly considered




Separated plutonium feed stream

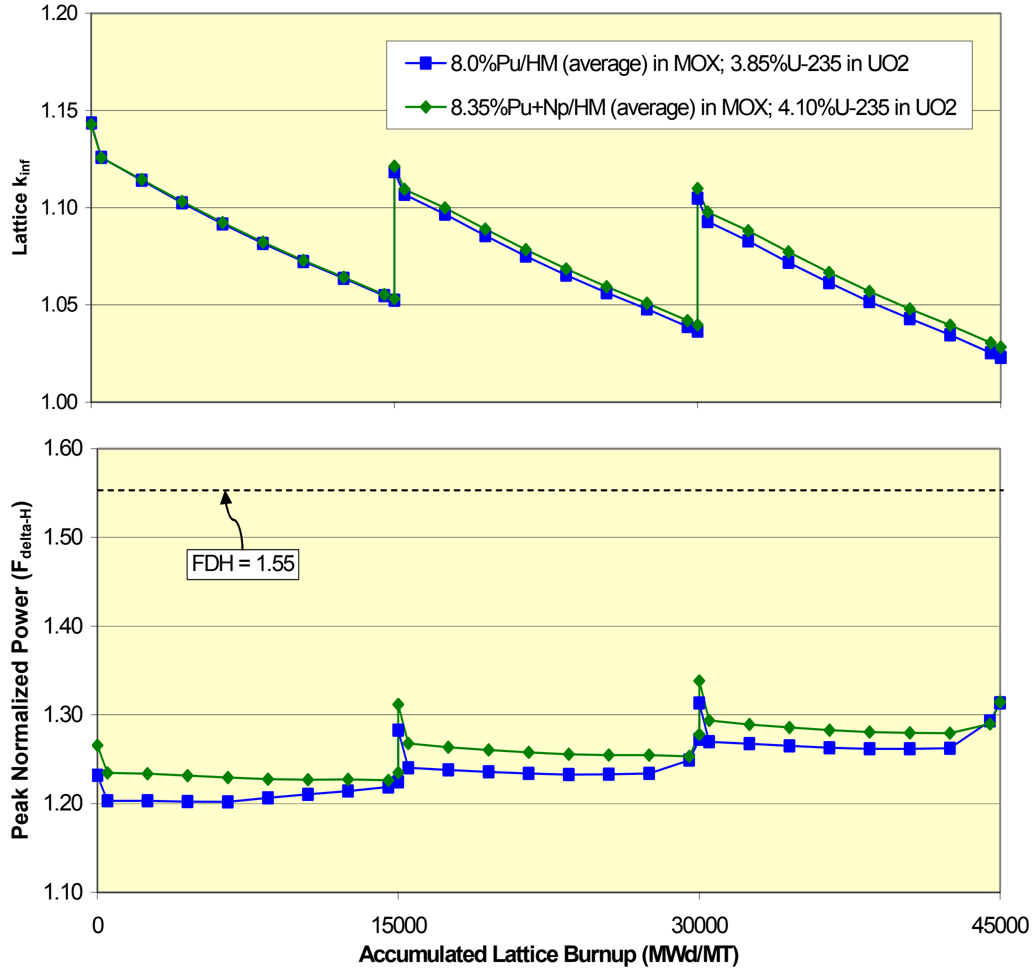



Plutonium plus neptunium feed stream

**Beginning of Cycle State in Mixed MOX/$UO_2$ Lattice**

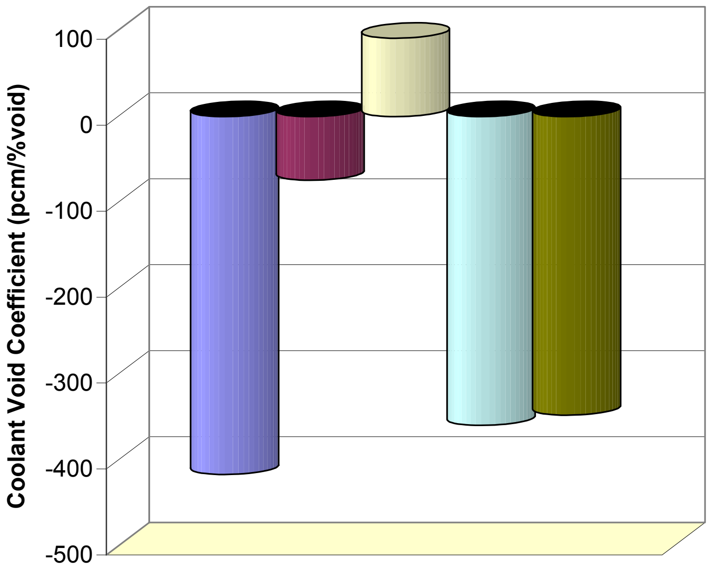
# Evaluation of MOX Fuel Performance (cont'd)

- **Power sharing between MOX and $UO_2$ assemblies relatively equal; discharge burnup difference between MOX and $UO_2$ < 6%**
- **Peak power occurs in fresh $UO_2$ assembly**
  - Demonstrates effectiveness of MOX pin loading optimization efforts
  - Without burnable poisons, peak $F_{\Delta H}$ = 1.486 and 1.506 for Pu-MOX and Pu+Np-MOX cases, respectively
  - For case with burnable poisons in fresh $UO_2$ (shown at right), peak $F_{\Delta H}$ is well below typical limit of 1.55




**Lattice $k_\infty$ and $F_{\Delta H}$ in Pu-MOX/$UO_2$ and Pu+Np-MOX/$UO_2$ Lattice**

# Reactivity Coefficient Estimates for Several Cores




All $UO_2$ core: 3.85 wt.%U-235

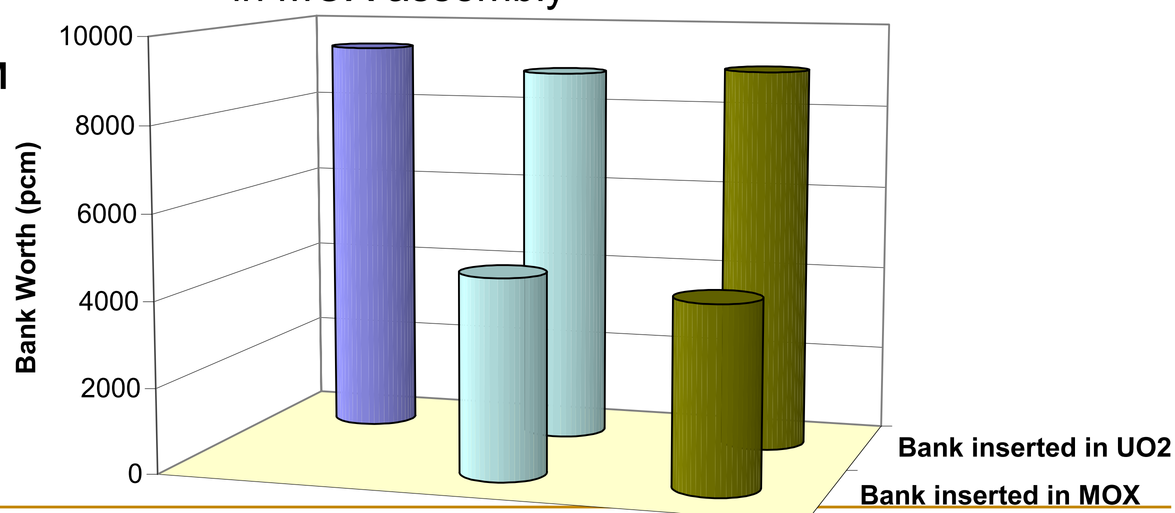
All Pu-MOX core: 9.5%Pu/HM

All Pu+Np-MOX core; 14.0%Pu+Np/HM

¼ Pu-MOX core: 8.00%Pu/HM (avg) in MOX, 3.85 wt.%U-235

¼ Pu+Np-MOX core: 8.35%Pu+Np/HM (avg) in MOX, 4.10 wt.%U-235

- **Coolant void coefficient (shown at left)**
  - Compared with all $UO_2$ core, void coefficient is 15-20% less negative for partial MOX core
  - All Pu+Np-MOX core has positive void coefficient
- **Control bank worth (shown below)**
  - Estimates based on standard bank ($B_4C$ material) inserted in 48 core locations
  - Control bank worth in $UO_2$ is 5% lower in mixed core
  - Control bank worth 30-50% lower when inserted in MOX assembly



# MOX Fuel Handling

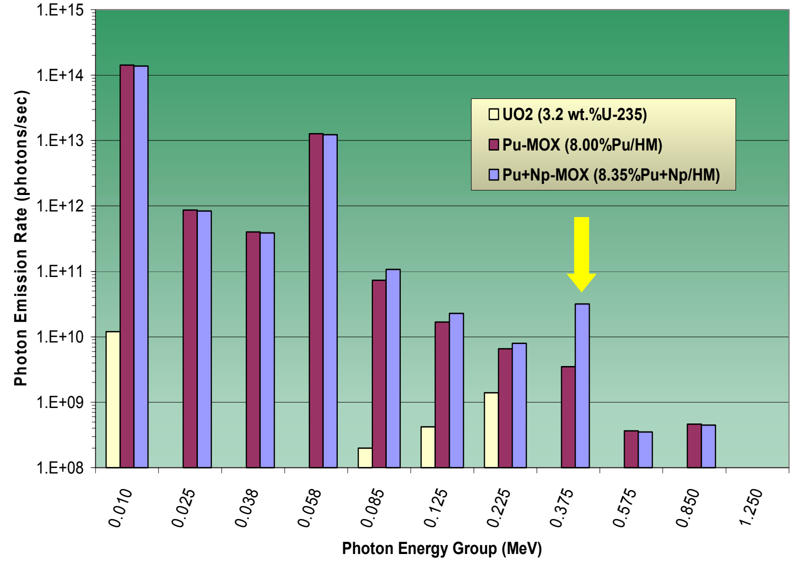
- **Decay heat generation in MOX assembly higher than $UO_2$, but not problematic**
  - Five year-cooled spent $UO_2$ assemblies (3 kW/assembly) stored in dry casks
  - Decay heat primarily from Pu-238 $\alpha$-decay ($t_{1/2}$ = 87.7 years)
- **Neutron source primarily from Pu-238 ($\alpha$,n) and Pu-240 spont. fission**
  - Neutron source slightly lower for Pu+Np-MOX due to displacement of plutonium by neptunium
- **However, photons are the most significant dose contributor, as long as americium and curium are not multi-recycled (Taiwo, *et al*)**

**Fuel Handling Indices for Charged Assemblies (Reactor charge assumed to occur two years after separation)**

| | | $UO_2$ (3.2 wt.%U-235) | Pu-MOX (8.00%Pu/HM) | Pu+Np-MOX (8.35%Pu+Np/HM) |
|---|---|---|---|---|
| Mass (kg HM) | | 461.3 | 461.3 | 461.3 |
| Decay Heat (Watts) | | 0.007 | 798 | 773 |
| Neutron Source (n/s) | Sp. Fission | 5.66E+03 | 1.56E+07 | 1.52E+07 |
| | ($\alpha$,n) | 5.23E+02 | 2.24E+07 | 2.17E+07 |

# MOX Fuel Dose and Proliferation Resistance

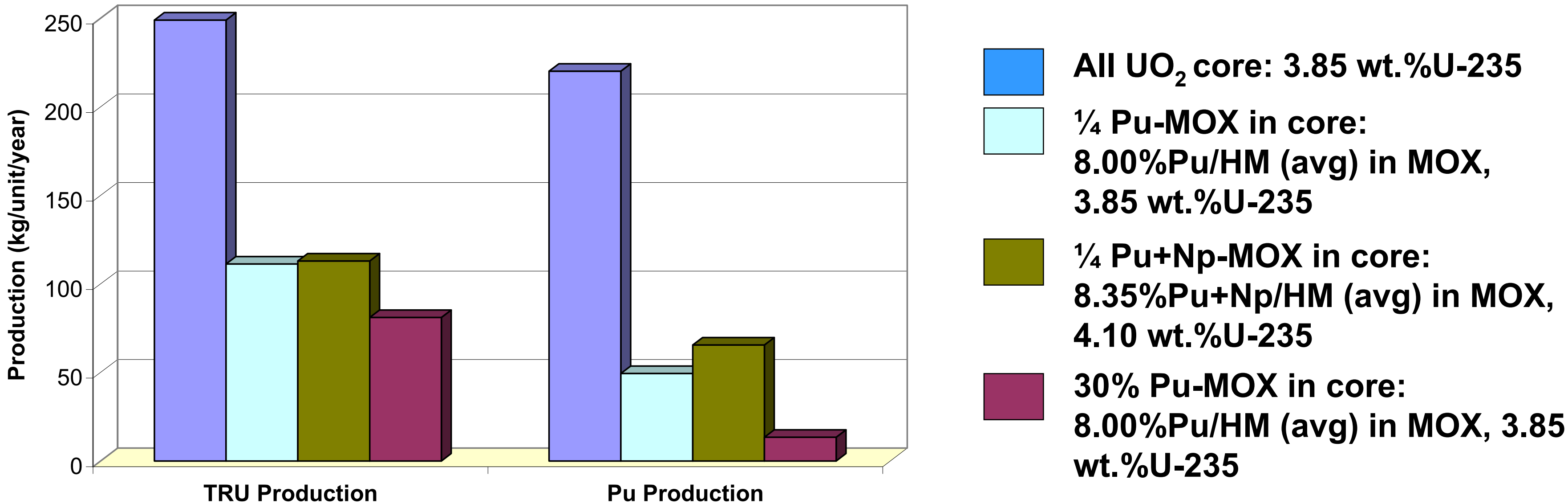
- **Recycling neptunium with plutonium increases source of higher energy photons due to $^{237}$Np $\rightarrow$ $^{233}$Pa $\rightarrow$ 312 keV $\gamma$**
- **Photon dose for MOX pins is 60% higher when neptunium is recycled**
  - Pin clad causes less attenuation of higher energy $\gamma$'s
  - Peak *assembly* dose at 1 meter is estimated to be < 8 mrem/hour
- **<u>Material contact dose is not increased by neptunium recycle</u>**
  - Dose is dominated by low energy photons from Pu-238, Am-241




**Photon Emission Spectra for $UO_2$, Pu-MOX, and Pu+Np-MOX Assemblies**

| Photon Dose Rates (mrem/hour) | | |
|---|---|---|
| | **Pu-MOX** | **Pu+Np-MOX** |
| **Pellet surface (*average*)** | **4204** | **4144** |
| **Pin surface (*average*)** | **80.1** | **130.1** |
| **1 Meter from pin (*peak*)** | **0.27** | **0.43** |

# *Transmutation Performance*




- **All $UO_2$-fueled core adds 250 kg TRU/year to spent fuel stockpile; 220 kg plutonium/year added to stockpile**
- **¼-Core MOX loading with mono-recycling significantly reduces production of transuranic nuclides per reactor unit**
  - All TRU production reduced by ~55%
  - Plutonium production reduced by 70-80%; less reduction for Pu+Np-MOX due to Np-237 → Pu-238 production
- **30%-Core Pu-MOX loading nearly balances plutonium production in $UO_2$ with consumption in MOX**

# Spent Fuel Isotopics

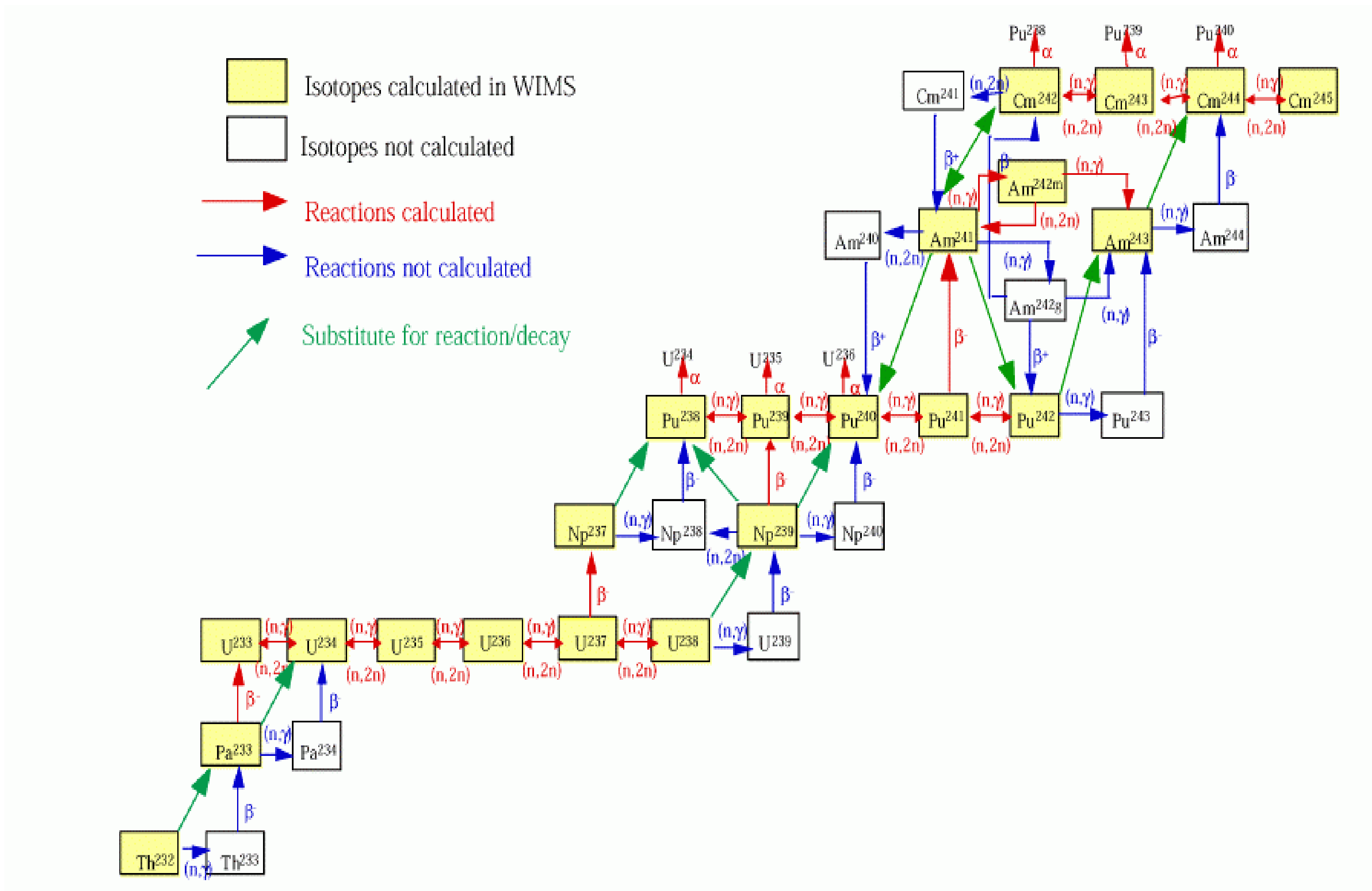
| | $UO_2$ | Pu-MOX | | Pu+Np-MOX | |
|---|---|---|---|---|---|
| **Nuclide** | 50 GWd/MT + 10 yrs. cooling | *Reactor Charge* | 45.2 GWd/MT + 10 yrs. cooling | *Reactor Charge* | 43.0 GWd/MT + 10 yrs. cooling |
| Am241 | 4.669% | *0.736%* | 7.237% | *0.684%* | 6.610% |
| Am242m | 0.019% | | 0.028% | | 0.026% |
| Am243 | 1.477% | | 2.111% | | 1.898% |
| Cm243 | 0.005% | | 0.008% | | 0.007% |
| Cm244 | 0.498% | | 0.740% | | 0.638% |
| Cm245 | 0.038% | | 0.117% | | 0.099% |
| Np237 | 6.663% | | 1.122% | *7.146%* | 5.693% |
| Pu238 | **2.758%** | *3.136%* | **3.759%** | *2.912%* | **6.368%** |
| Pu239 | 48.813% | ***56.380%*** | **36.192%** | ***52.350%*** | **34.435%** |
| Pu240 | 23.056% | *26.626%* | 30.393% | *24.723%* | 27.751% |
| Pu241 | 6.949% | *7.290%* | 9.248% | *6.769%* | 8.408% |
| Pu242 | 5.050% | *5.832%* | 9.044% | *5.416%* | 8.066% |

- **MOX recycle destroys transuranic nuclides, and also alters the character of the remaining TRU**
  - Significant reduction of Pu-239 content
  - Increase in Pu-238 content, particularly with neptunium recycle
    - *Elevated decay heat and neutron source may add proliferation resistance; this barrier is only associated with Pu in spent MOX fuel*

# Conclusions

- Enrichment zoning in MOX can be optimized to reduce power peaking
- Enthalpy-rise hot-channel factor ($F_{\Delta H}$) < 1.55 achieved in partial-MOX core for both separation/fabrication scenarios
- For Pu+Np-MOX, parasitic capture in neptunium increases uranium enrichment requirements
- Coolant void coefficient in partial-MOX core is 15-20% lower (less negative) than for all $UO_2$ core
- Compared with all $UO_2$ core, control rod worth is 5% lower if inserted in $UO_2$, and 30-50% lower if inserted in MOX
- Plutonium production and consumption is balanced with ~1/3-core loading of MOX; however, current spent fuel stockpile will support an aggressive mono-recycling campaign (i.e. in all units) for only ~15 years
- Neptunium recycling does not increase MOX contact dose: *no additional intrinsic proliferation resistance at the separations or fabrication plants*
- Neptunium recycling increases MOX pin dose rate by 60%, but assembly dose rate is still quite small (<8 mrem/hour at 1 meter)
- Conversion of recycled Np-237 to Pu-238 “denatures” the Pu vector in spent MOX fuel, which may make it less attractive to proliferators

# WIMS8 Actinide Depletion Chain



# Benchmarking of Np+Pu W Assembly Calculations @ BOL

- K-inf=1.31958 (WIMS)/1.3331±0.0003 (MCNP)
- % Difference in Pin-Power (1-σ errors in MCNP ~1%)

Box Power 1.016(WIMS)/1.021(MCNP) 0.855/0.845

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 2.3 | 1.6 | 0.0 | 0.4 | 0.1 | 0.0 | -0.4 | -2.3 | -1.5 | 2.7 | 0.0 | -1.3 | -2.8 | 0.0 | -0.7 | 0.5 |
| -0.4 | 1.4 | 0.3 | 0.1 | 1.9 | 0.8 | -0.3 | -1.1 | -1.7 | 0.6 | -0.9 | -0.8 | -0.4 | -0.2 | -0.9 | -0.1 | 0.6 |
| -1.6 | 0.8 | 1.1 | 0.2 | 1.6 | 0.4 | -1.1 | -0.6 | -0.1 | 1.6 | -0.1 | -1.5 | 2.2 | 2.3 | -2.9 | 0.8 | 0.0 |
| 0.0 | 0.4 | -1.2 | 0.0 | 0.0 | -0.3 | 0.0 | -1.1 | -0.5 | -2.6 | 2.4 | 0.0 | -0.6 | -0.9 | 0.0 | -1.7 | -1.2 |
| -0.5 | 0.7 | 1.5 | 0.7 | -1.3 | -0.6 | -2.0 | 0.8 | 0.1 | -0.4 | -1.2 | -3.2 | -1.2 | 0.5 | -0.8 | 1.5 | 2.7 |
| 0.3 | 0.3 | 0.8 | -0.3 | -1.0 | 0.0 | -0.8 | -1.2 | -0.9 | 0.4 | 0.7 | 1.3 | 0.0 | -1.0 | -0.4 | 1.1 | 1.2 |
| 0.0 | 0.0 | -1.2 | 0.0 | 0.3 | -0.5 | 0.3 | 0.0 | -1.0 | 0.5 | 0.8 | 0.3 | 1.9 | 0.3 | 0.0 | -0.6 | 1.1 |
| -0.7 | -0.3 | -0.9 | -0.5 | 0.9 | 0.7 | 0.9 | -0.9 | -0.4 | -0.4 | 0.0 | 1.5 | -1.2 | -0.5 | 1.6 | 1.4 | -0.2 |
| 0.7 | 0.6 | 0.7 | 0.9 | 1.4 | 0.4 | 0.9 | -0.4 | -0.9 | 0.5 | 1.7 | -0.2 | -0.7 | 0.6 | -0.9 | 0.5 | 0.1 |
| 2.0 | -0.4 | 0.2 | 0.0 | 1.0 | 0.8 | 0.5 | 0.5 | 0.2 | 0.2 | 0.1 | -0.7 | -0.5 | 0.9 | 0.0 | 0.0 | -0.1 |
| 0.4 | 0.6 | 0.7 | 0.2 | 0.1 | -0.5 | 0.8 | 0.2 | -1.2 | 1.0 | 0.5 | 0.7 | -0.4 | -0.8 | -1.1 | 1.1 | -1.0 |
| 0.0 | -0.4 | -0.8 | 0.0 | -0.9 | -1.0 | 0.3 | -0.1 | -0.4 | 0.7 | 1.0 | 0.0 | 0.0 | -0.3 | 0.0 | -1.0 | -0.9 |
| -0.8 | 0.7 | 2.0 | -1.0 | -1.8 | 0.0 | -0.4 | 0.6 | 0.7 | 0.5 | 1.0 | 1.0 | 0.0 | -0.8 | -1.0 | -0.5 | -0.9 |
| -1.2 | 0.9 | 0.3 | -0.5 | -0.8 | -0.6 | 0.1 | 0.8 | 1.0 | 1.2 | 0.6 | 0.3 | -0.3 | 0.0 | -2.2 | -0.7 | 0.4 |
| 0.0 | -0.3 | -0.8 | 0.0 | 0.0 | -1.7 | 0.0 | -0.2 | -0.1 | -0.2 | -0.5 | 0.0 | -0.7 | -0.6 | 0.0 | -1.2 | 0.0 |
| -0.9 | 0.2 | -0.1 | -1.0 | 0.9 | -0.8 | 0.2 | 0.4 | 1.6 | 0.1 | 0.9 | 0.7 | 1.0 | 0.6 | -0.3 | 0.9 | 0.6 |
| -0.6 | -0.4 | 0.7 | -0.5 | 1.0 | 0.5 | -0.8 | 0.0 | 1.5 | 1.7 | 1.0 | -0.7 | -0.1 | 1.5 | -0.1 | 1.4 | -0.1 |
| 0.0 | -1.0 | 0.1 | 0.0 | -0.4 | -0.7 | 0.0 | -0.1 | 0.1 | 1.2 | -0.2 | 0.0 | -1.3 | 0.1 | 0.0 | -1.1 | -0.6 |

1.114/1.112 1.016/1.021

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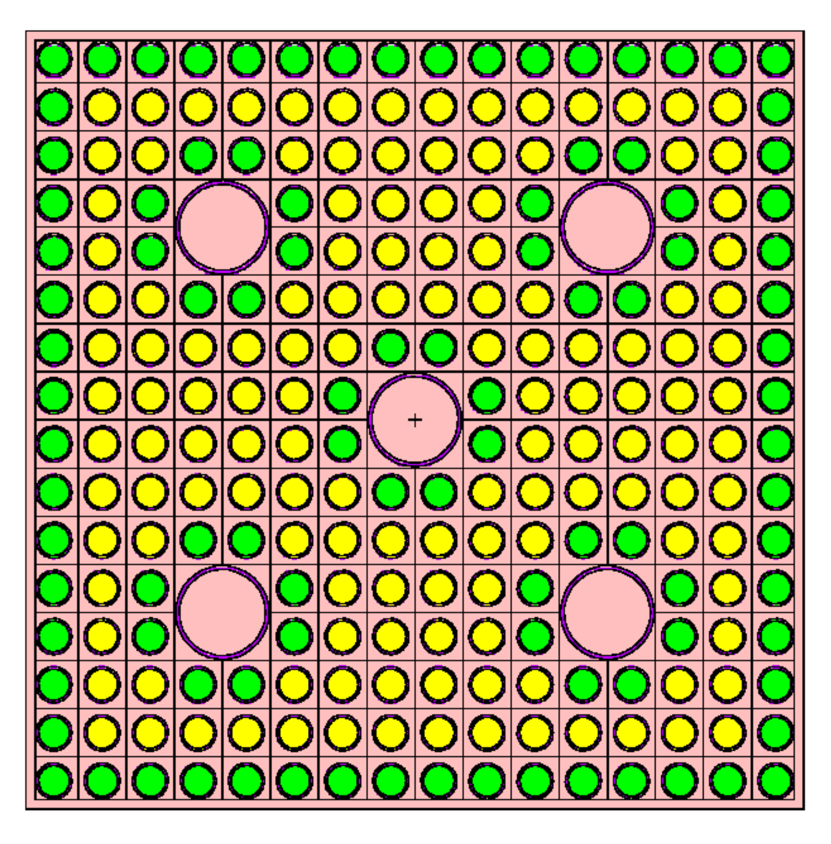
# CE System-80

- **CE-System-80 Plants Designed for Full-Core MOX $\rightarrow$ option for AFCI**
  - MCNP & DRAGON models developed and initial benchmarking completed
  - K-inf and power distributions in reasonable agreement
- **Design Calculations Underway**
  - Homogeneous and heterogeneous configurations
  - Performance with burnup
  - Reactivity coefficients



# Reduced Moderator Water Reactor (RMWR)

- Hard spectrum of RMWR makes it interesting for AFCI (potential for transmutation)
- Neutronic and Thermal-Hydraulic Benchmarks proposed by JAERI
- One-group cross-sections from rod-cell provided for D-factor analyses to CEA
- Calculations for neutronic benchmarks are underway
- Calculations for AFCI applications underway (BOC and burnup)

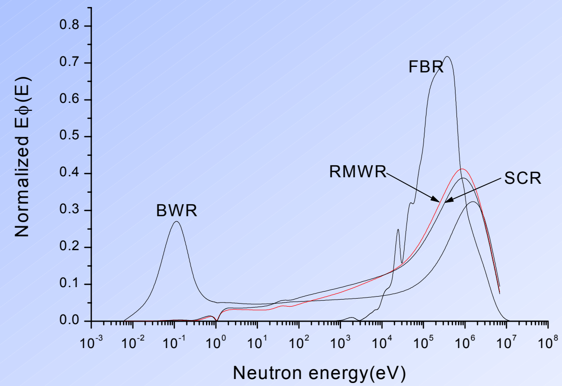
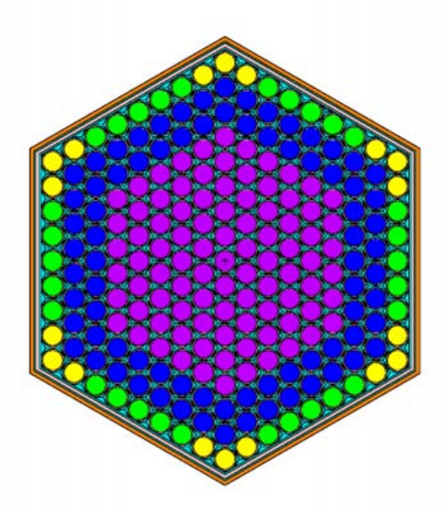



**Fig. 5** Comparison of AHCLWR spectra for typical BWR and FBR



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# JAERI Rod-Cell Benchmark

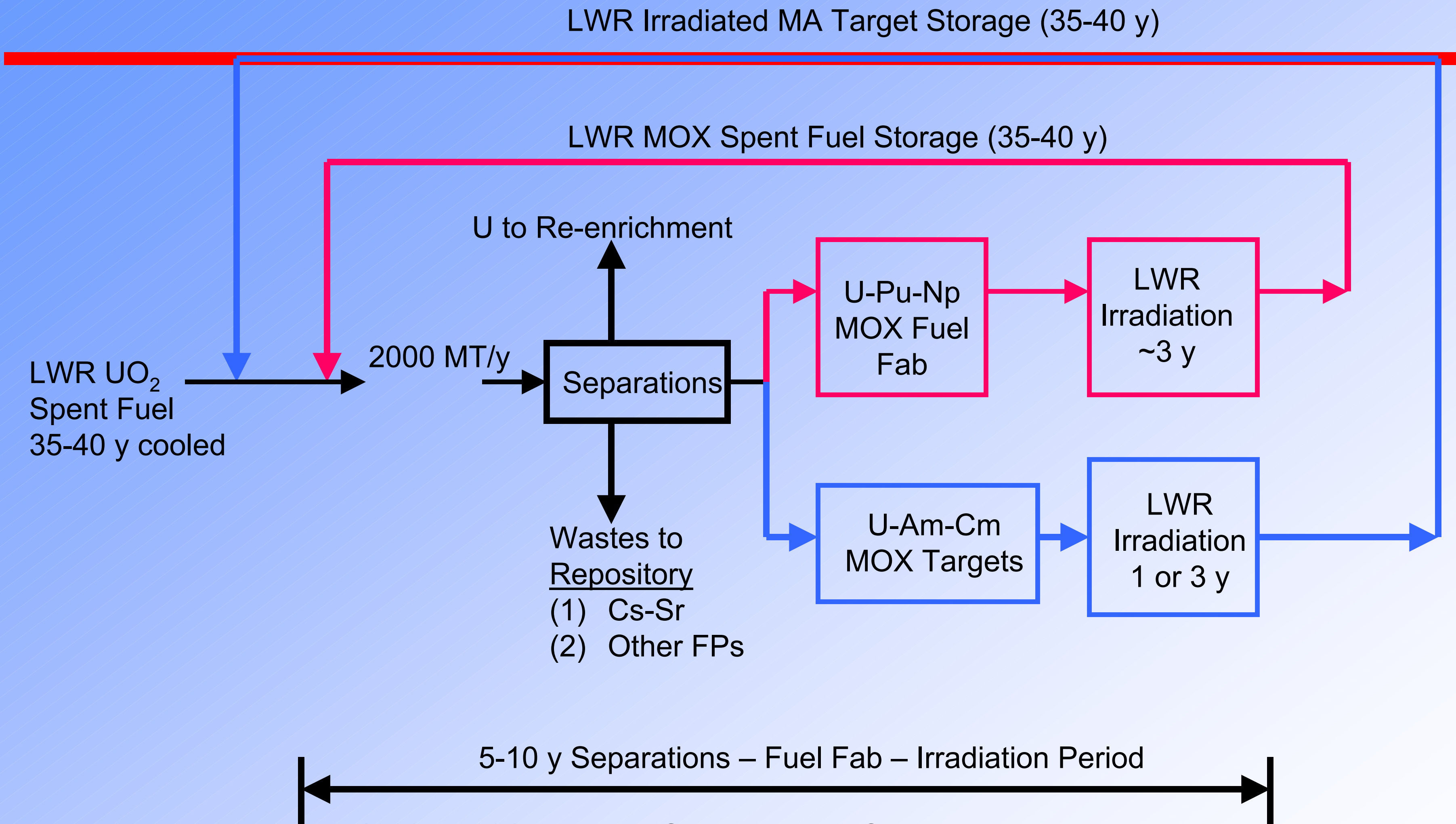
Room Temperature; Moderator Void Fraction 0.5

| | ENDF/B-VI (DRAGON 69G is WIMS86) | | | | JEF2.2 | |
|---|---|---|---|---|---|---|
| | MCNP4C | DRAGON (69G/172 G) | HELIOS (190 G) | $MC^2$-II (230 G) | MCNP4C | WIMS8 (172 G) |
| 1.43cm Rod-Pitch | $1.572 \pm 0.001$ (reference) | 1.561/1.564 (-0.8/-1.1) | 1.577 (+0.5) | 1.570 (-0.2) | $1.536 \pm 0.001$ (-3.6) | 1.548 (-2.4) |
| 1.4cm Rod-Pitch | 1.5918$\pm$0.0006 | 1.583/ | | | | |

## Significant MA reduction can be achieved in LWRs using MA Target strategy

- **Assumptions:**
  - 2000 MT/yr pocessing of 35-40yr-cooled LWR fuel
  - Am/Cm processed into pins w/5% LEU or inert diluent
  - Pu/Np processed into U-Pu-Np pins for 1/3 MOX cores
  - 3yr irradiation w/3mo or 3yr cooldown between 18mo shuffle
  - 35-40 yr cooldown (use oldest LWR SF first)

- **Results:**
  - 95% consumption of Am in target rods w/ inert diluent or 87% reduction for LEU diluent
  - At least 2 cycles possible before needing higher enrichment
  - Hence, keep MA out of repository for at least additional 75-80 yrs




1960s – 2015: LWR $UO_2$ Irradiations Only

2015 – 2055: LWR $UO_2$ + LWR MOX 1st Cycle Irradiations

2055 – 2095: LWR $UO_2$ + LWR MOX 2nd Cycle Irradiations